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Woods Hole Oceanographic Institution

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A [illegible] GRAVIMETER STABLE PLATFORM SLAVED TO THE [illegible] MARK 19

by

J. P. Dean

August 1972

TECHNICAL REPORT

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13 ABSTRACT

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Details of illustrations in this document may be better studied on microfiche

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2. GEON						
3. Stable platform						

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ABSTRACT

Measurement of the gravity vector at sea requires stable platforms for a gravimeter and a celestial theodolite. A repeater platform slaved to the GEON Mk 19 can fulfill these requirements for the VSA gravimeter, leaving the master gyrocompass system free for the theodolite. The Mk 19 synchro roll and pitch outputs are utilized to drive the slave table, which is constructed to be carried underneath the Mk 19 and physically coupled to its reference support frame. The synchro-synchro-servo loops are stabilized by inverse feedback of the resonant frequencies resulting in the loop amplifier acting as a band reject filter.

INTRODUCTION

Marine Physical Geodesy is the measurement of the gravity vector at sea. This entails measurement of both magnitude of gravity and the deflection of the vertical from normal to the reference spheroid. The instrumentation and technique for measurement of the direction is discussed by von Arx, 1971, using GEON, (Gyro Erected Optical Navigation) and he referred to the Vibrating String Accelerometer (VSA) gravimeter for measurement of gravity magnitude (Wing, 1969).

There is the requirement that both the theodolite used in the celestial navigation at sea and the gravimeter be supported by an accurate stable platform, and the Sperry Mk 19 Mod 3c (modified) satisfies these requirements. However, the Mk 19 is a complex mechanical and electrical system and is costly to acquire and maintain. The theodolite and the gravimeter because of physical size require separate platforms. There is the additional requirement that the equipment be housed in a portable laboratory sufficiently small in size and weight to be handled by a research ship's loading equipment. The obvious advantages are that the laboratory can be outfitted ashore and placed on a ship <u>en masse</u> for measurement purposes. Also since the nature of this work at present is to run specific experiments rather than general surveying, the portable labs are seldom used on any particular ship for an extended period of time. The portable lab concept allows for transportation by air or over land to and from remote parts if desirable.

These restrictions require that to measure magnitude and direction, two or more labs must be used and two stable platforms secured and maintained.

On the other hand, if a sufficiently small stable platform which requires small amounts of power, dissipates little heat and occupies a small space is available to support the gravimeter, then it is possible to use a single lab to measure both parameters. Such repeater designs are common and the required servo design is not new. The space limitations and fund constraints however dictate that it be a special mechanical design.

DESIGN APPROACH

The GEON stable platform provides roll and pitch position data via synchro data transmitters and if a small repeater platform were built to follow these inputs and mounted underneath the Mk 19 but integrally coupled to the reference frame it would be out of the way and occupy otherwise unused space. This repeater table (or slave table) would follow exactly or be "slaved" to the master system.

The general specification for such a slave table is that it align and continuously maintain stability to the local vertical under all conditions. The instantaneous gravimeter off-level error at 3 arc minutes is 0.4 milligals but the observed error would depend on the dynamic environment and the filtering inherent in the VSA system. The modifications

which have been made to the GEON Mk 19 Stable platform have reduced its servo following error to the order of two-tenths of a minute, therefore the prime source of error is that introduced by the data transmitters and the repeater, slave table, itself. Gravimeter errors due to accelerations (horizontal) are caused by the interaction of off-level resulting from servo following error and horizontal accelerations related to ship's motions and location of the stable platform on the ship. In theory these motions are 90° out of phase and roughly sinusoidal in form. As a result they tend to be negligibly small when the MK 19 is used as the stable platform (Wing, 1969). The GEON Mk 19 utilizes angular accelerometers to further reduce the following errors and the repeater slave table re-introduces errors no larger than those compensated for by the angular accelerometer inputs. Static leveling error can be reduced virtually to zero because the gravimeter itself can be used to level the table.

ELECTRICAL CONSIDERATIONS

The electrical design approach is straightforward. Each axis is required to have a synchro control transformer compatible to the 400 hertz synchro transmitters of the master system. These control transformer outputs must be demodulated and amplified to drive a dc-torque motor which positions the axis. The loop must be sufficiently "tight" so that no error

signal representative of more than 15 seconds of arc is required to drive the axis at maximum velocity. The amplifier gain and stabilization technique for the loop must be established. A repeater system of this sort is rather interesting in that the repeater table is really not driven at all. Once the reference position is initially established the servo loop simply maintains position and must overcome the torque due to friction and horizontal acceleration. In truth the ship moves about the platform and the platform simply maintains position. The horizontal acceleration force is related to the unbalance or pendulosity of the table and it would appear desirable to have the driven mass perfectly balanced thus reducing the effects of horizontal acceleration to zero. Slight pendulosity however, lends control to the off-power condition, and provides sufficient positioning accuracy at an initial turn-on to eliminate the necessity for self-synchronization through the use of a two speed synchro system.

The optimum amount of pendulosity depends on amplifier gain, torquer capability, and horizontal acceleration, which in turn depends on the ship's roll and pitch characteristics (a function of sea state) and location of the stable platform on the ship.

It was determined that electronic damping via amplifier inverse feedback be employed. Gain and damping controls enable the use of a common amplifier design for both the roll and pitch axes and allow adjustments for varying monents of inertia

which could result from changing the table load. The desired result was achieved by securing off-the-shelf power operational amplifiers and adding the feedback networks and demodulators. Power available is 115 volts, 60 or 400 hertz, and the amplifiers' self-contained dc power supplies may be connected to either source.

MECHANICAL CONSIDERATIONS

The mechanical design is more of a challege. The basic goal is a set of gimbals that are strong, small, lightweight and inexpensive, designed to mount underneath the present GEON system, large enough to hold the VSA and its oven. The structural integrity of the design must be sufficient so as to introduce no additional error into the system due to flexure of the gimbals.

Aluminum castings seemed to provide the solution but because of the cost of the drawings, patterns and machining the casting to tolerances required, another solution was sought. The answer lay in the construction of an assembly of aluminum tubing and stress free cast aluminum jig plate blocks which had been machined completely as individual components prior to assembly. This combination of parts assembled in proper alignment with epoxy adhesive provide a light, strong and stable gimbal ring requiring no machining after assembly. Developing techniques for bending the tubing and applying and curing the adhesive so as to insure no stress concentrations was the major challege. Stress concentrations in a section of the assembly could result in mechanical creep and resultant misalignment. The adhesive

chosen was 2-part epoxy per MIL-A-8623-A, type I. Gimbals were assembled in true alignment but with clearance between metal parts to allow the adhesive to form the bond and cure stress-free. The technique involves the use of a base block with precision machined orthogonal holes. Stainless steel drill rod is then used to couple the gimbal components to the block. Figure 1 illustrates an inner ring with the tools in place. The epoxy used is available in three viscosities, one of which is highly thixotropic and will not flow at the curing temperature of 180°F.; and is used to "tack" the assembly together. After the first application has cured the more viscous epoxy is used to fill the void completely by applying the adhesive to the pre-heated aluminum utilizing gravity flow. It is important that the aluminum be clean and free from excess oxide in order to achieve proper bonding of the adhesive. Chemical film treatment of aluminum chromate was used as a primer for the table components. This treatment is easy to apply and is quite satisfactory as a primer as well as providing corrosion protection. It is available under several brand names, (ALCHROME #2, IRIDITE #14-2, ALIDINE).

The slave table is integrally coupled to the Mk 19 reference frame by removing the hard shock mounts and installing the slave table supports. These supports extend through the base of the gyrocompass and form a symmetrical three point mount for the slave table. The hard shock mounts are not used in the GEON system because they transmit mechanical noise from the

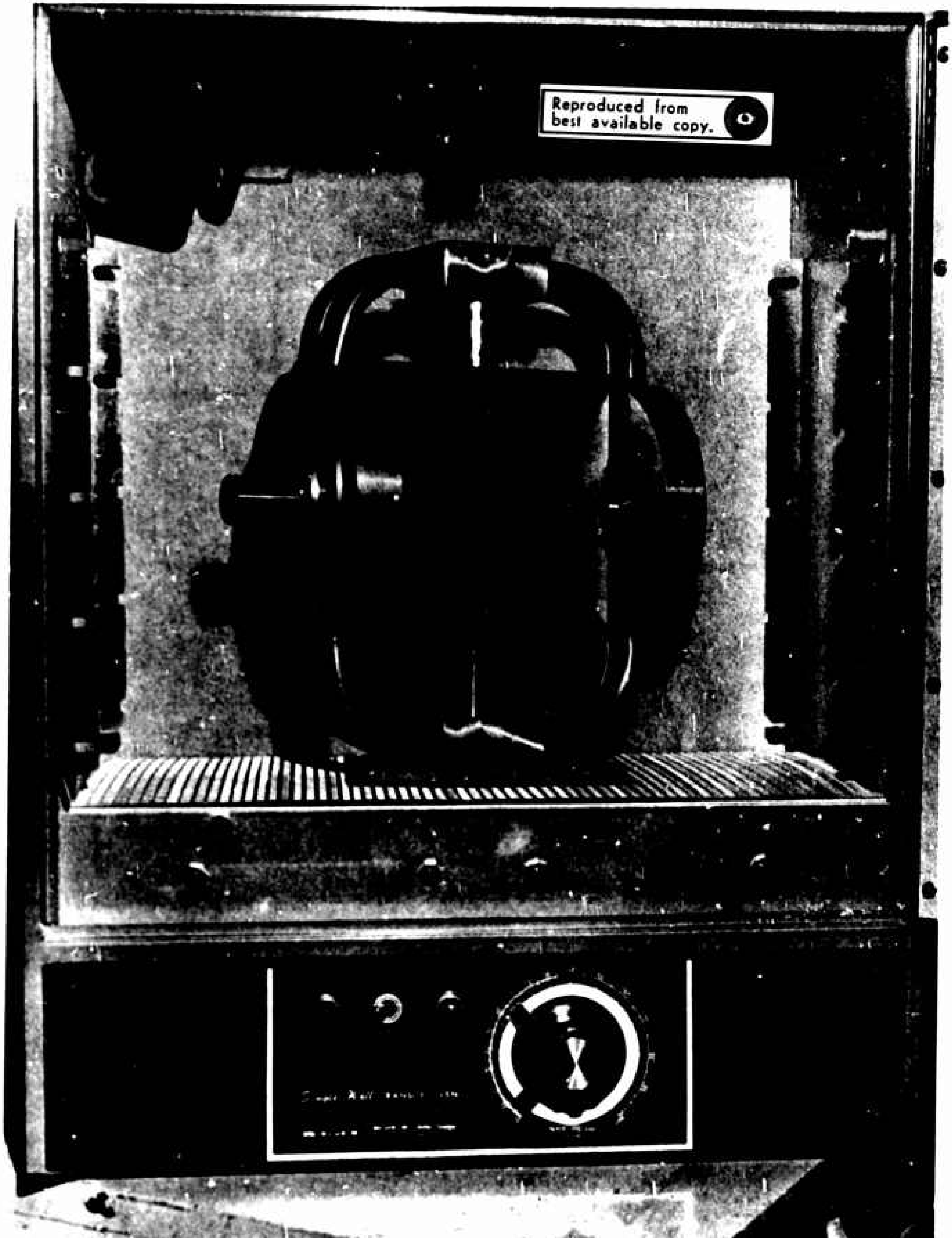
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Figure 1.

ship to the optics and the system is equipped with rubber shock mounts which provide necessary support.

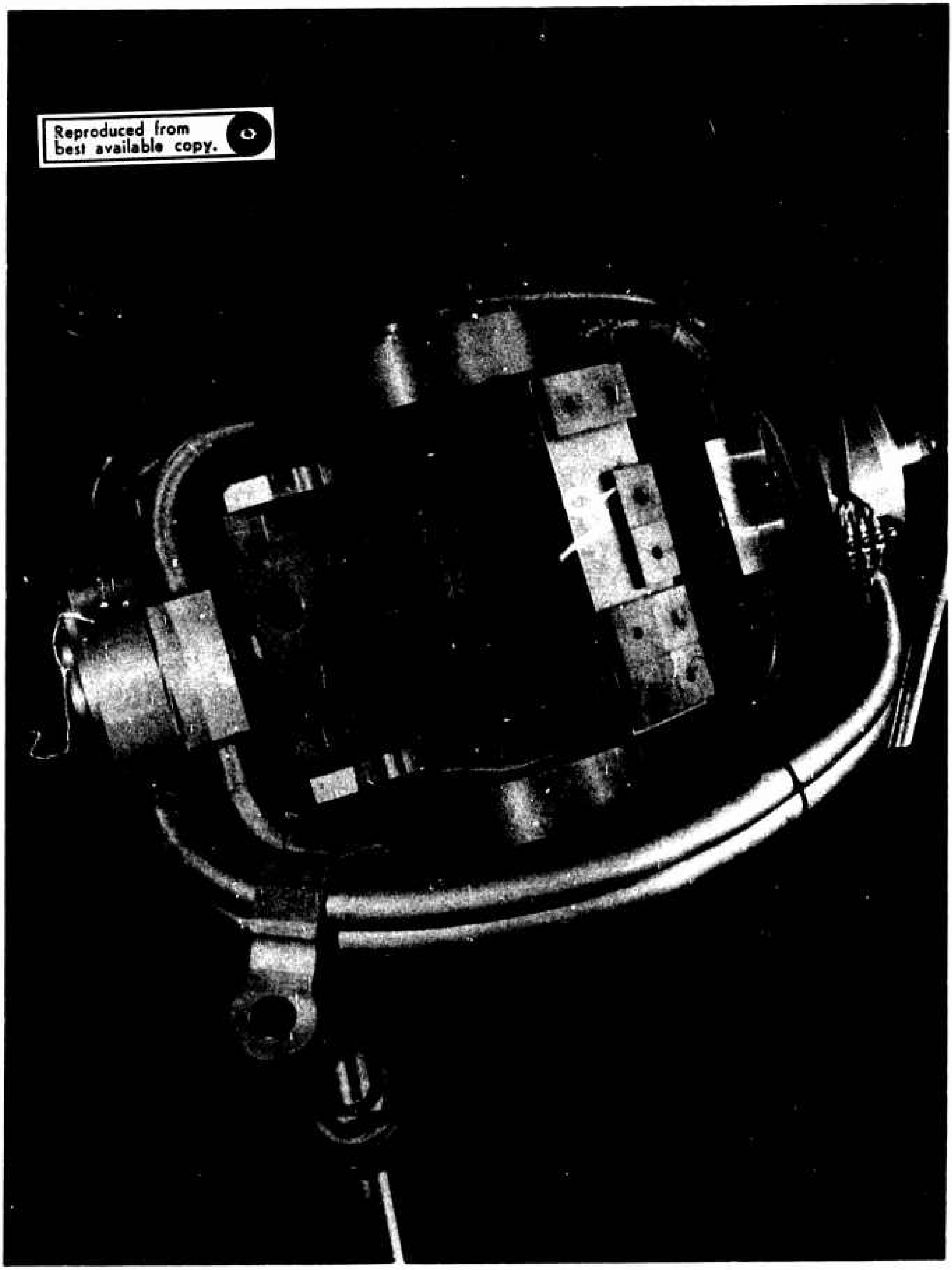
Figure 2 is a top view of the slave table showing the gimbal arrangement and the gravimeter mounting surface with dove-tail. Holes in the mounting surface and the weights shown on the top are used to facilitate desired balance of the table when the gravimeter is installed.

Figures 3 and 4 are other views of the slave table with the VSA gravimeter installed. The ruler shown in the lower right of Figure 4 is a six inch scale.

Figure 5 is a view of the slave table mounted under the GEON Mk 19 master compass assembly. Figure 5A is a view of the electronics unit.

OPERATION

Figure 6 is a schematic representation of the Mk 19 stable platform with the slave table added. The roll and pitch followup motors drive the gimbal ring and phantom to maintain alignment between these members and the gyro gimbals. The signal sources for the followup motors are the roll and pitch pickoffs in each gyro, and this signal is resolved in the roll and pitch resolver then amplified to drive the servo-motors. Geared to the motors and gimbals are roll and pitch synchro transmitters. These devices transmit electrical signals representative of shaft position which is transformed again



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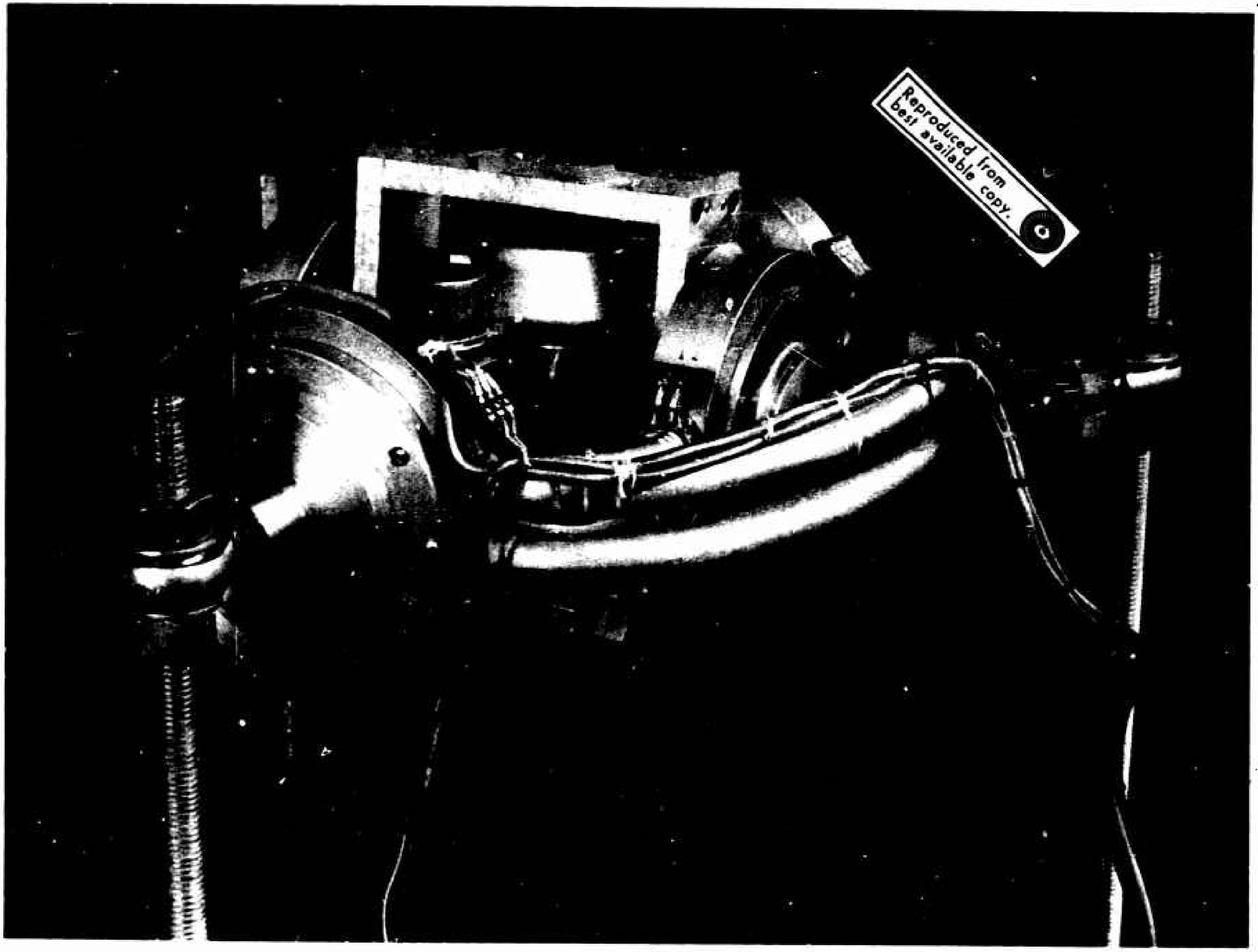

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Figure 3.

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Figure 4.

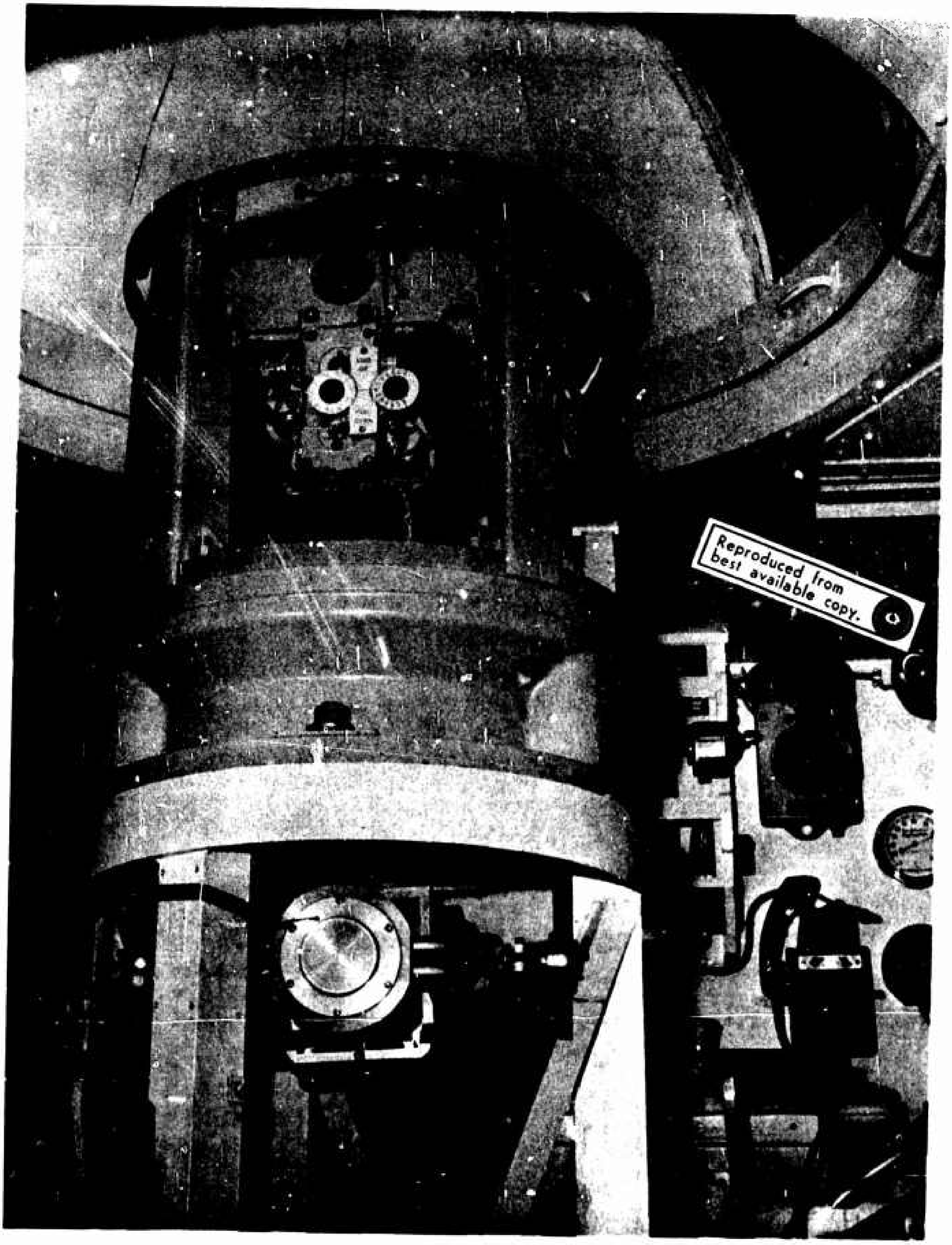
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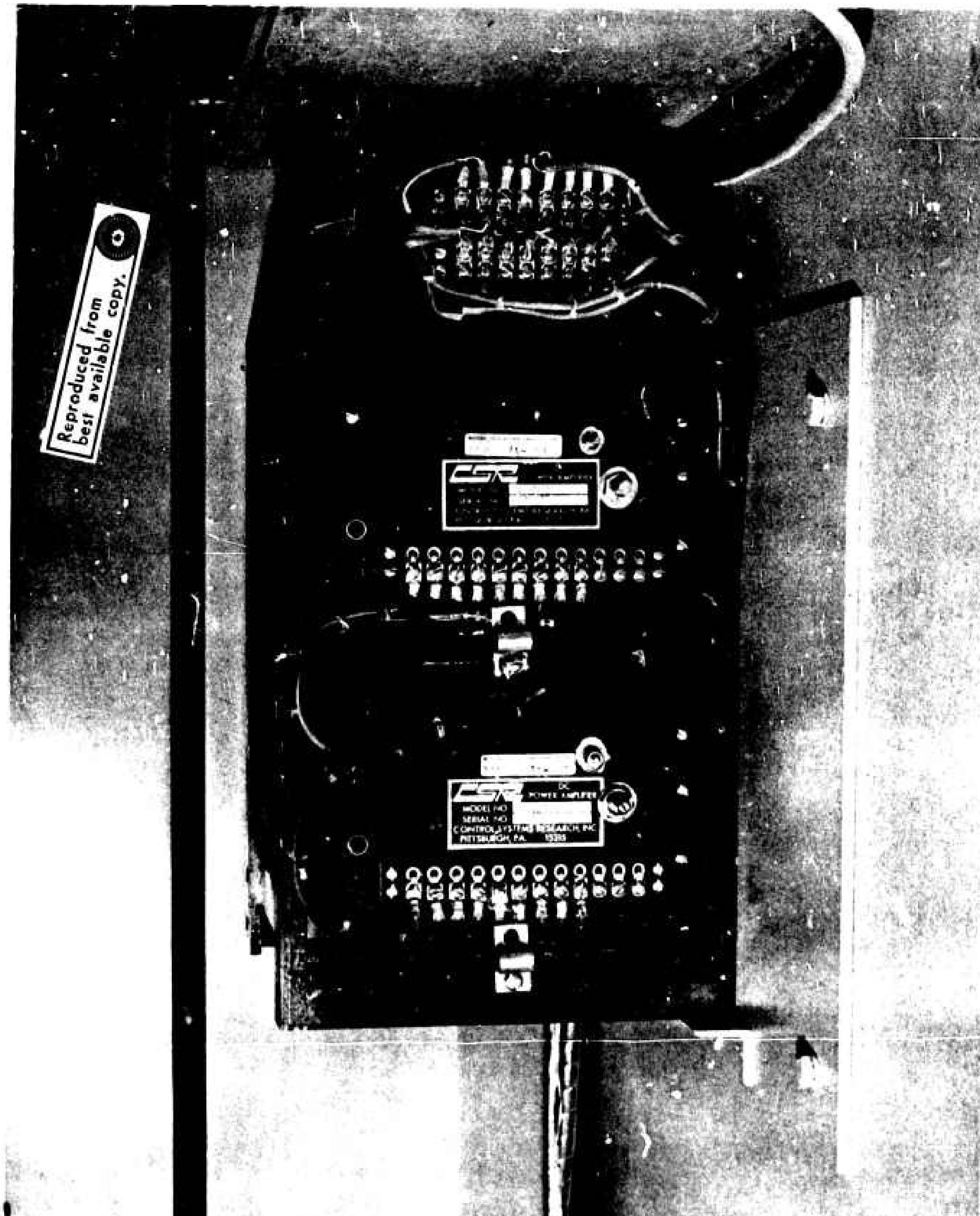
Figure 5.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CSR
DC POWER AMPLIFIER
MODEL NO
SERIAL NO
CONTROL SYSTEMS RESEARCH, INC
PITTSBURGH, PA.

Figure 5A.

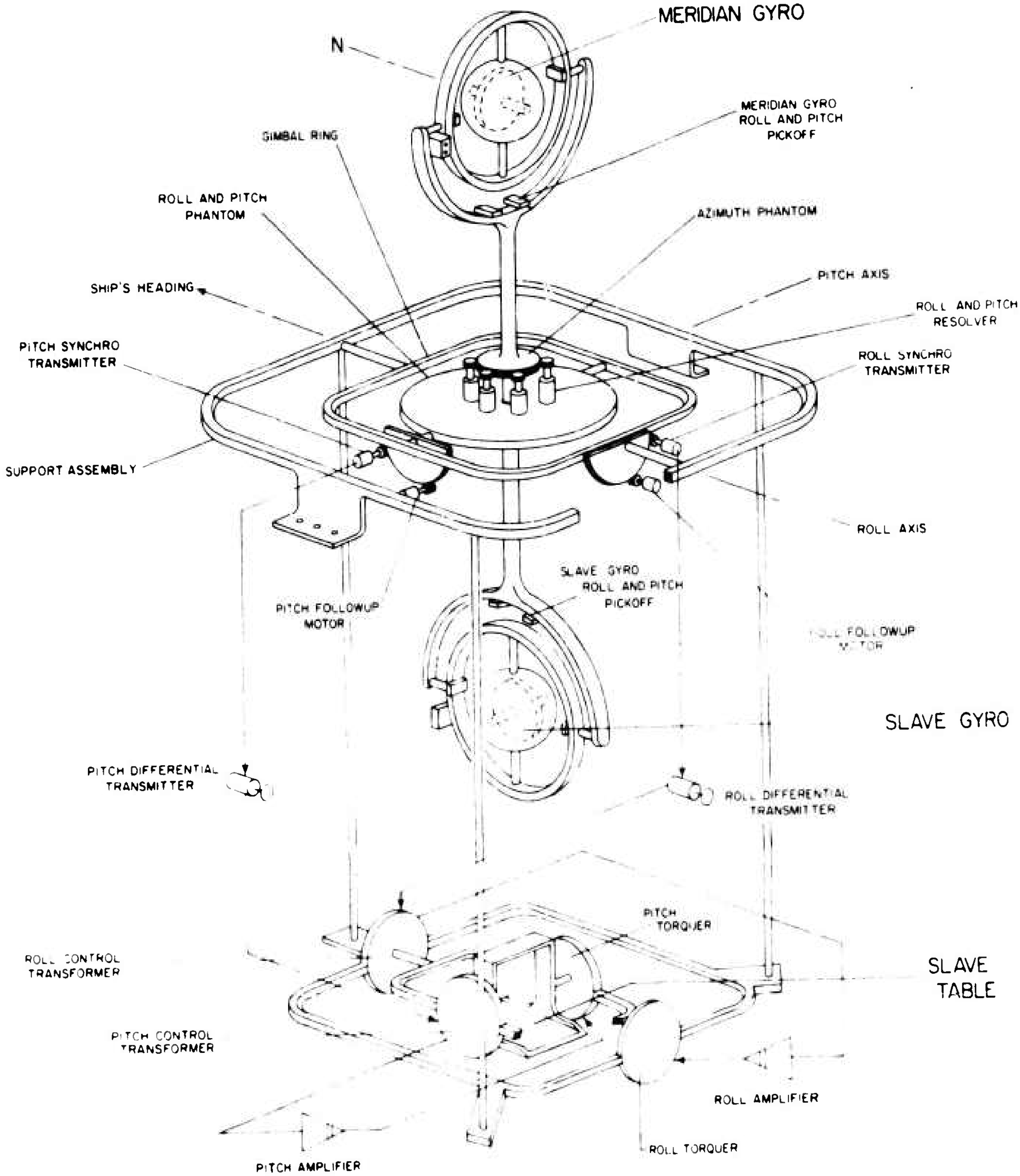
MERIDIAN GYRO
N
MERIDIAN GYRO
ROLL AND PITCH
PICKOFF
GIMBAL RING
ROLL AND PITCH
PHANTOM
AZIMUTH PHANTOM
SHIP'S HEADING
PITCH AXIS
ROLL AND PITCH
RESOLVER
PITCH SYNCHRO
TRANSMITTER
ROLL SYNCHRO
TRANSMITTER
SUPPORT ASSEMBLY
ROLL AXIS
SLAVE GYRO
ROLL AND PITCH
PICKOFF
PITCH FOLLOWUP
MOTOR
SLAVE GYRO
PITCH DIFFERENTIAL
TRANSMITTER
ROLL DIFFERENTIAL
TRANSMITTER
PITCH
TORQUER
SLAVE
TABLE
PITCH CONTROL
TRANSFORMER
ROLL AMPLIFIER
ROLL TORQUER
PITCH AMPLIFIER

Figure 6.

to position in the slave table servo loop. A block diagram of this synchro-synchro-servo loop which repeats the Mk 19 gimbal position on the slave table is shown in Figure 7. The roll and pitch loops are identical except for damp and gain control settings which are adjusted for optimum dynamic operation.

The three wire synchro position data are transmitted from the Mk 19 to a synchro differential transmitter. This device provides for adjustments in the table position, leveling adjustment to align the gravimeter's sensitive axis to the vertical irrespective of gravimeter mounting surface accuracy. The slave table responds to changes in shaft position of either the data transmitter or the differential transmitter. The signal is then applied to the slave table control transformer (CT). The output of this device is a 400 hz signal whose amplitude and phase sense are proportional to the magnitude and direction of misalignment between the master reference and the slave table. This signal is then processed (phase rectified) by a demodulator and fed as dc to the power amplifier which drives the table axis via the torque motor. The control transformer shaft is coupled to the torque motor and thus the loop is closed; the motor drives the CT shaft in the proper direction to maintain "null" electrical output. The error signal required from the CT to drive the motor is dependent on the gain in the loop and the higher the

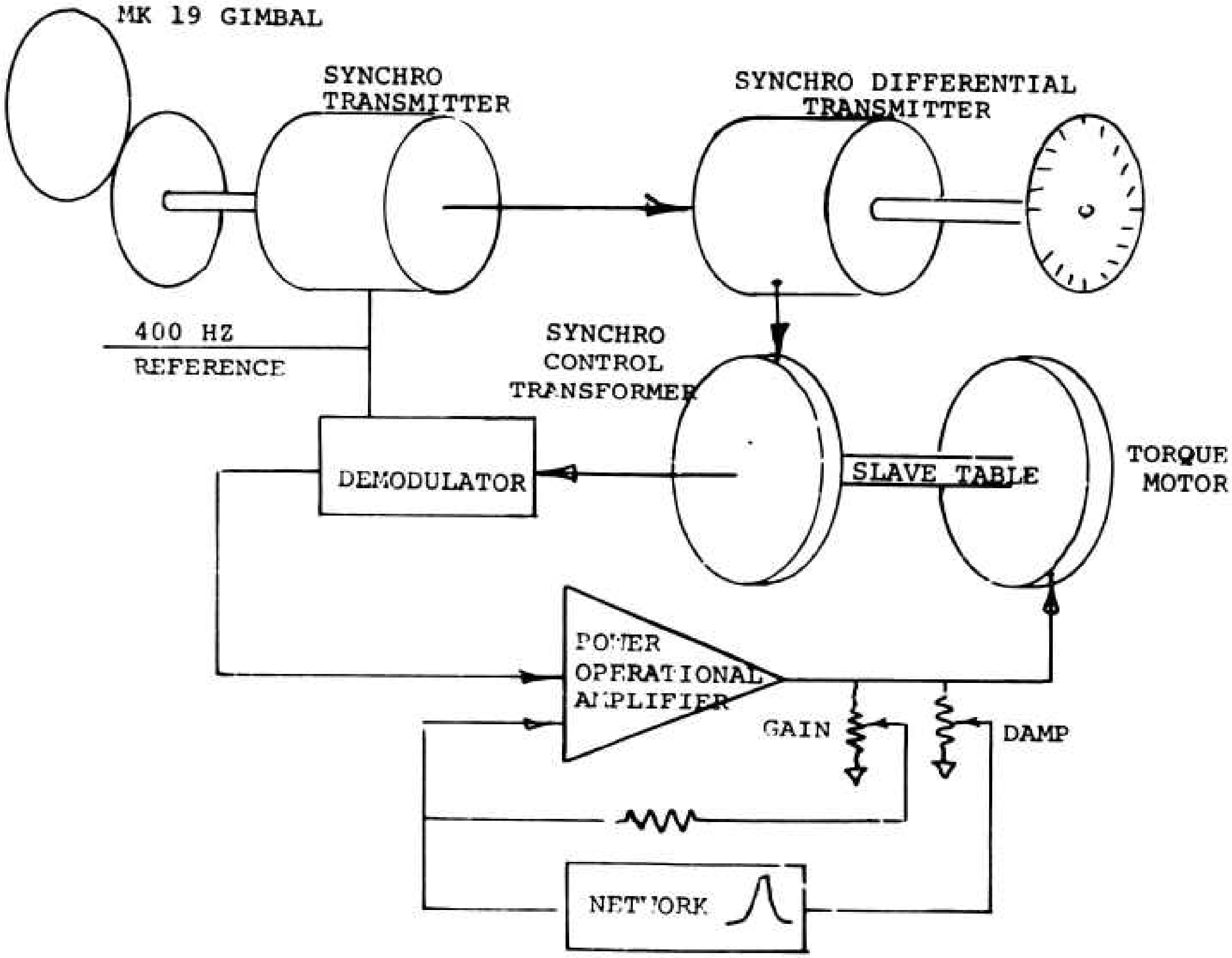
MK 19 GIMBAL
SYNCHRO TRANSMITTER
SYNCHRO DIFFERENTIAL TRANSMITTER
400 HZ
REFERENCE
SYNCHRO CONTROL TRANSFORMER
DEMODULATOR
SLAVE TABLE
TORQUE MOTOR
POWER OPERATIONAL AMPLIFIER
GAIN
DAMP
NETWORK

Figure 7.

gain the "tighter" the loop.

In general it is desirable to have higher loop gain in a servo system under static (or steady state) conditions than a flat broadband amplifier will allow. The motor responds to the slightest stimulus and drives the control transformer shaft; and in the absence of some damping means will overshoot the null position. This overshoot will cause a change in direction but the motor will again drive past the null resulting in a sustained oscillation at the natural frequency until the gain is reduced. This frequency depends on the physical characteristics of the gimbals, bearings and motor inherent damping. In fact the natural frequency can be determined in such a loop by closing the loop as described above and measuring the frequency of oscillation. The loop can then be stabilized by providing a notch in the frequency response of the amplifier at the natural frequency of the loop so that the gain is substantially reduced at this frequency.[1.]

Both gimbals of the slave table have natural frequencies of about 3 hertz and Figure 8, curve A, shows the open loop

1. For a thorough treatment of servomechanism theory the reader is referred to "Servomechanism Practice" by W. R. Ahrendt, McGraw-Hill or "Servomechanisms and Regulating Systems Design" by H. Chestnut and R. W. Mayer, John Wiley & Sons.

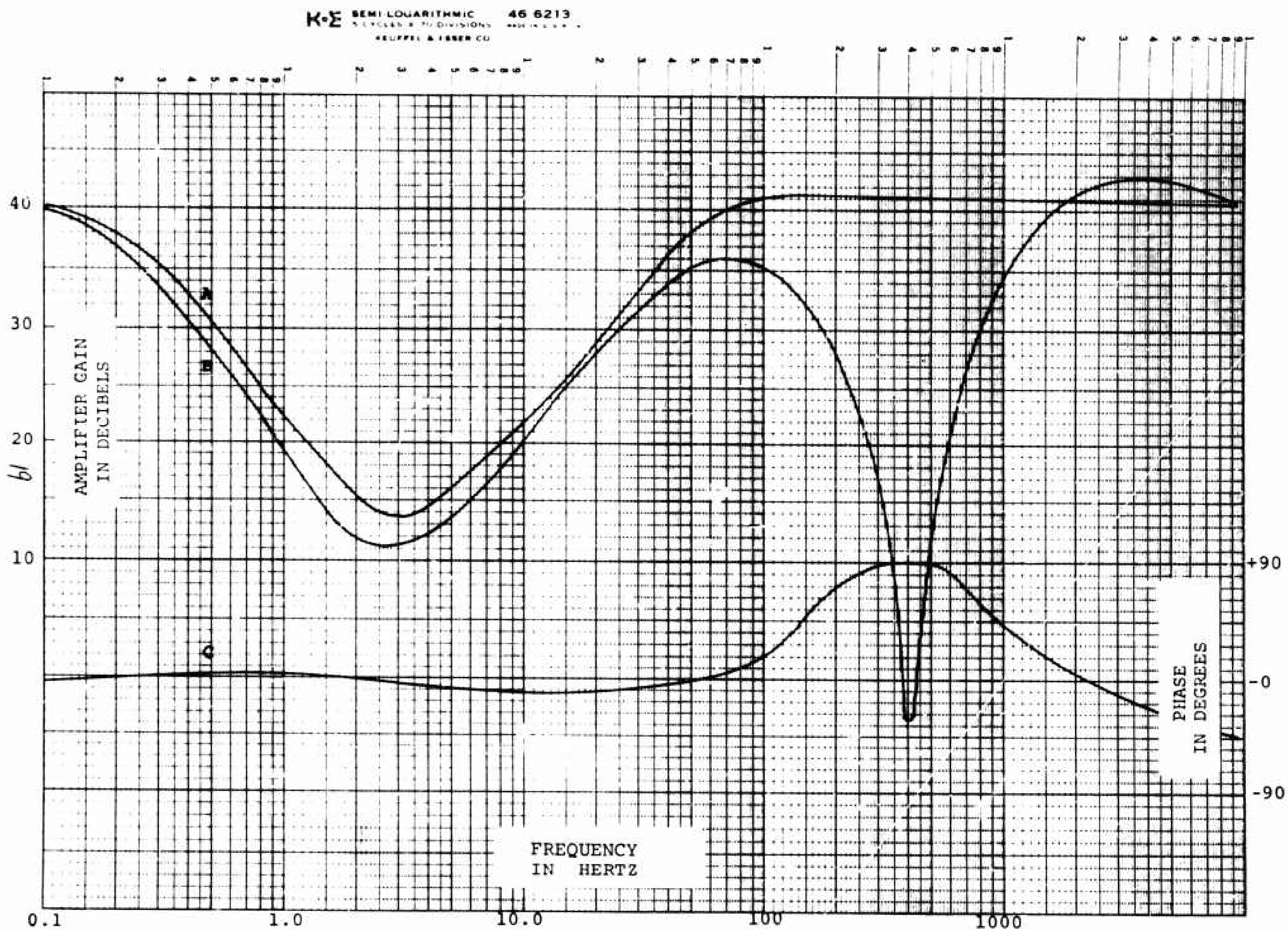
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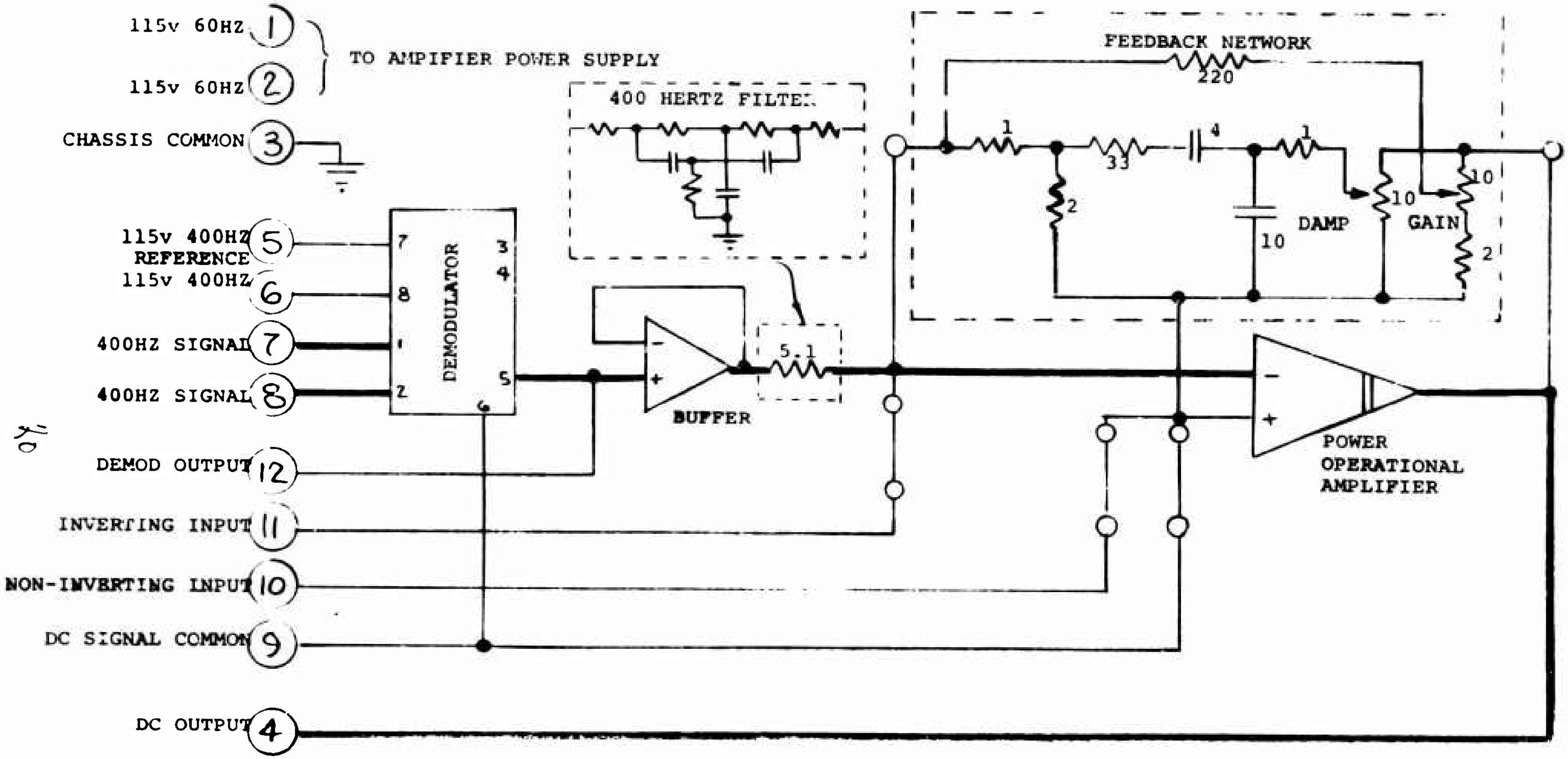
Figure 8.



RESISTANCE IN KILOHMS

CAPACITANCE IN MICROFARADS

Figure 9.

response of the slave table amplifiers with a notch centered about 3 hertz. Curve B of Figure 8 includes a notch at 400 hertz in the event there is very high 400 hertz noise in the environment and a filter is needed. This in no way degrades performance of the slave table. Curve C is the phase relationship between input and output signals.

Figure 9 depicts the circuitry used to provide the 3 hz notch and also provide gain and damping control. The network is a two pole band pass filter circuit used in the inverse feedback loop of an operational amplifier providing what has been termed a band reject active filter.

The amplifier consists of a power operational amplifier (Control Systems Research, Inc. Model 100PMA) to which the demodulator, a buffer amplifier, and the feedback network has been added. Both roll and pitch amplifiers are identical and gain and damp control adjustments can be made to compensate for slight differences in the loop characteristics.

CONCLUSIONS

The resulting instrument is simple to operate and maintain, and because of its simplicity is inherently reliable. Calibration of the gravimeter is a simple matter because the platform can be inverted precisely 180° and held there electronically through the synchro-servo loop. Tilting tests are easily run by the use of the control differential transmitters

in the data lines, and re-adjusting the verticality, if necessary, can be done by the same means.

General characteristics of the device are tabulated in Figure 10, and Figure 11 gives the position error to be expected for a typical dynamic case. The instantaneous horizontal acceleration given is that which may be expected on a ship rolling or pitching 20 degrees with an 8 second period and with the stable platform located 5 metres above the axis of rotation of the ship.

The static accuracy of the slave table itself is no better than 10 arc seconds due to basic imprecisions in the synchros. Of more significance is that dynamic off level error introduced by the mechanical imperfections in the Mk 19 gimbal position detection; which when coupled with the gyro verticality may produce a total instantaneous error which is of the order of an arc minute.

Figures 12 and 13 are slave table assembly drawings and show the interior construction of the device and the method employed to mechanically couple the instrument to the Mk 19 master compass.

CHARACTERISTICS

Control Transmitter/transformer		
Sensitivity	20.6	volts/radian
Error	6.0	arc mins
36X sensitivity	0.78	v/mrad
Error	10	arc sec
Demodulator		
Gain	5.0/3.2	v.dc/v.ac
Saturation level	4	mrad (12 arc min)
Amplifier		
Gain (adjustable)	40-240	v/v
Saturation level	1	mrad (3 arc min)
Torque Motor		
Sensitivity	3.75	oz-in/volt
Resistance	20	ohms
Max current	1.3	amps
Max voltage	26.0	volts
Output power	34	watts
Max no load velocity	43	rad/sec
Friction	4	oz-in

Figure 10.

TYPICAL DYNAMIC CONDITIONS

Pendulosity	100	oz-in
Horizontal acceleration	0.1	g
Total friction (worse case)	10	oz-in
Amplifier gain	100	v/v
Demodulator gain	1.5	v/v

Pendulous torque = pendulosity x horizontal acceleration

= 100 oz-in/g x 0.1 g

= 10 oz-in

Error volts = (torque + friction)/motor sensitivity

x 1/amp gain x 1/demodulator gain

= 20/3.7 x 1/100 x 1/1.5

= 0.036 volts

Position error = error volts / CT sensitivity

= 0.036 volts / 0.78 volts/mrad

= 0.028 mrad ($\cong$10 arcsec)

Figure 11.

ACKNOWLEDGEMENTS

The following people made significant contributions to this work: Mr. A. T. Spencer, who did all the machining and provided much valuable help and advice; Mrs. Coyla McCullough, who provided clerical assistance; and Dr. W. S. von Arx, who provided the opportunity. The project was supported by ONR contract #N00014-66-241 NR083-004.

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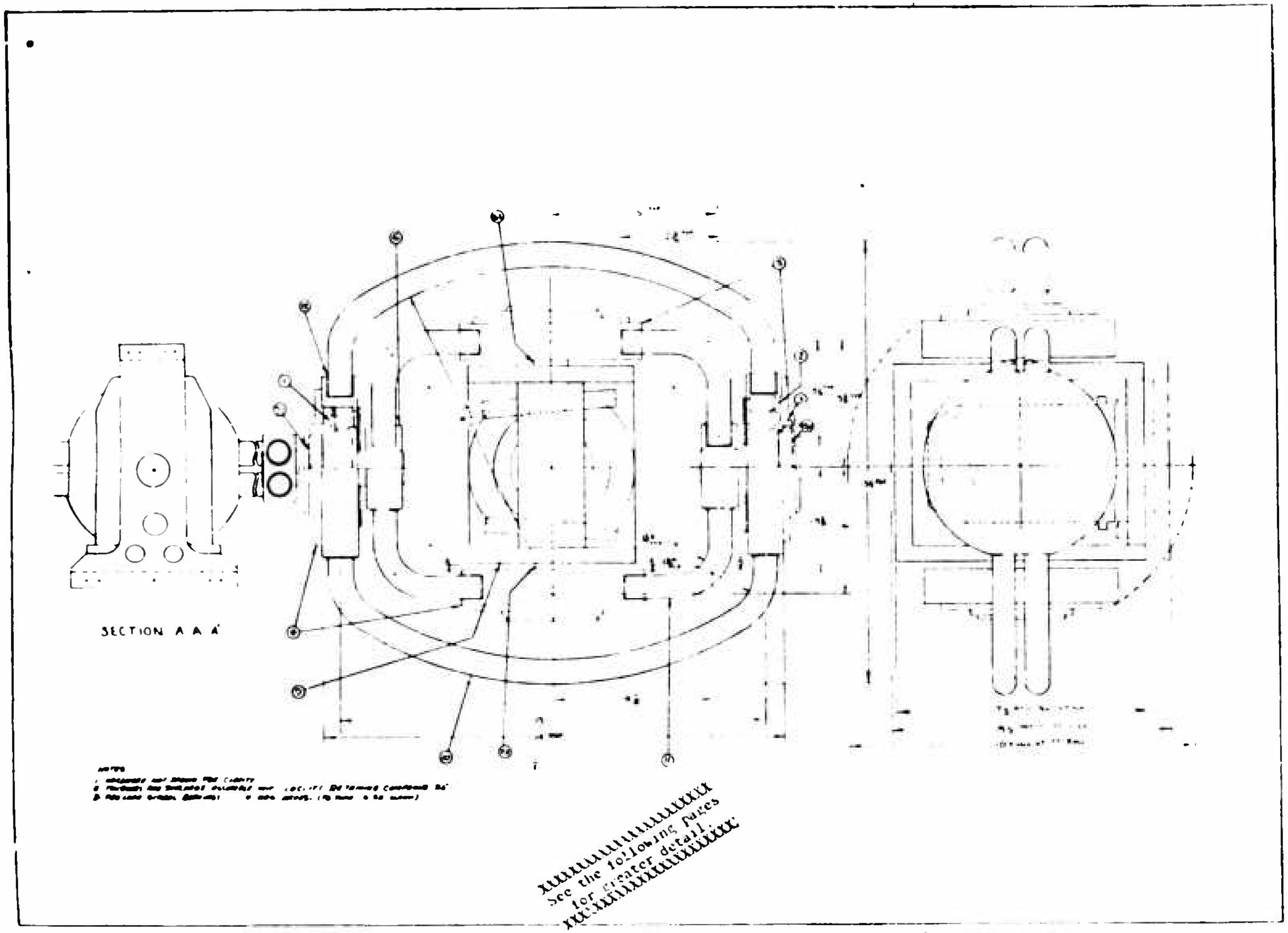
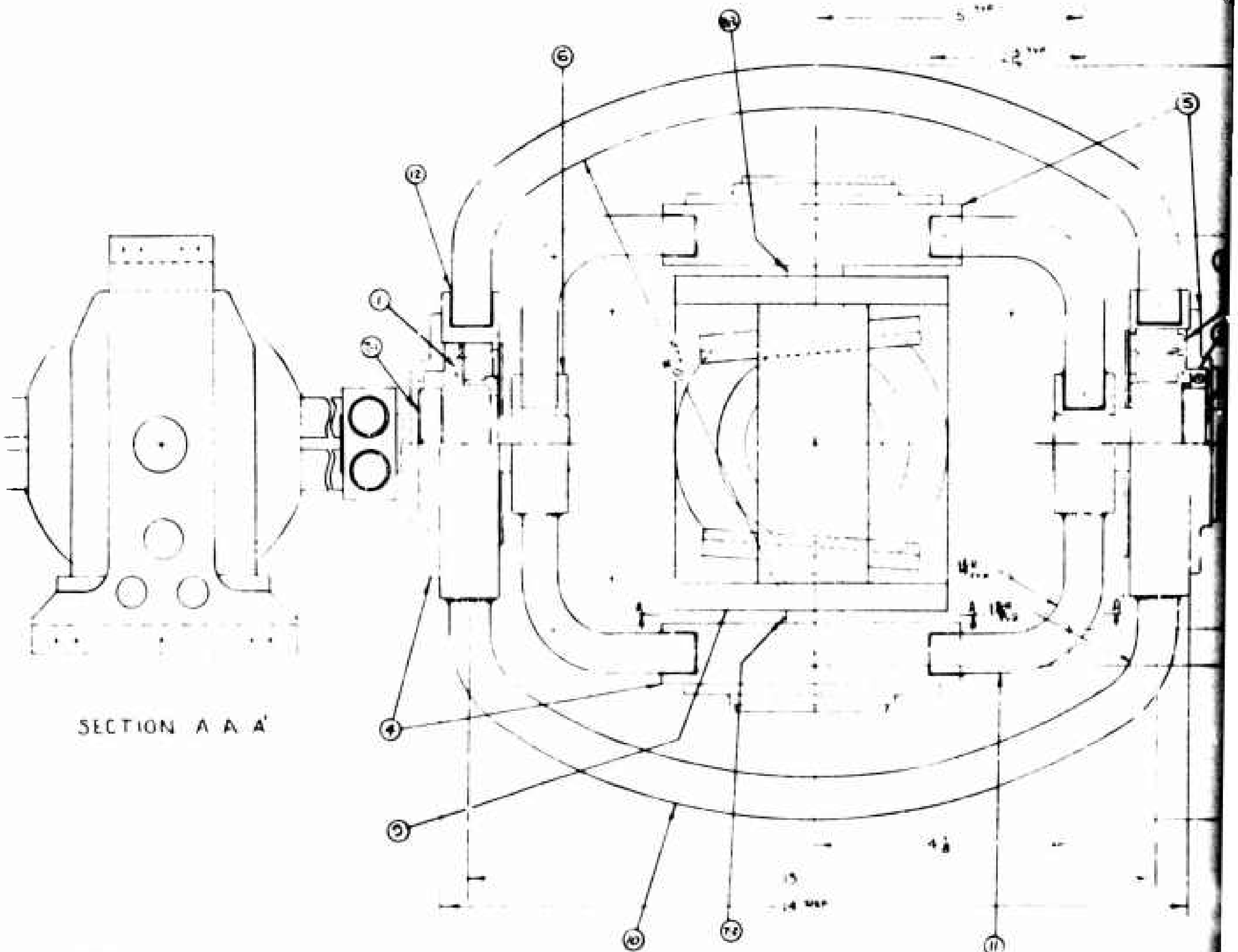


26.1

Figure 12.

26.2



NOTES
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Figure 12.

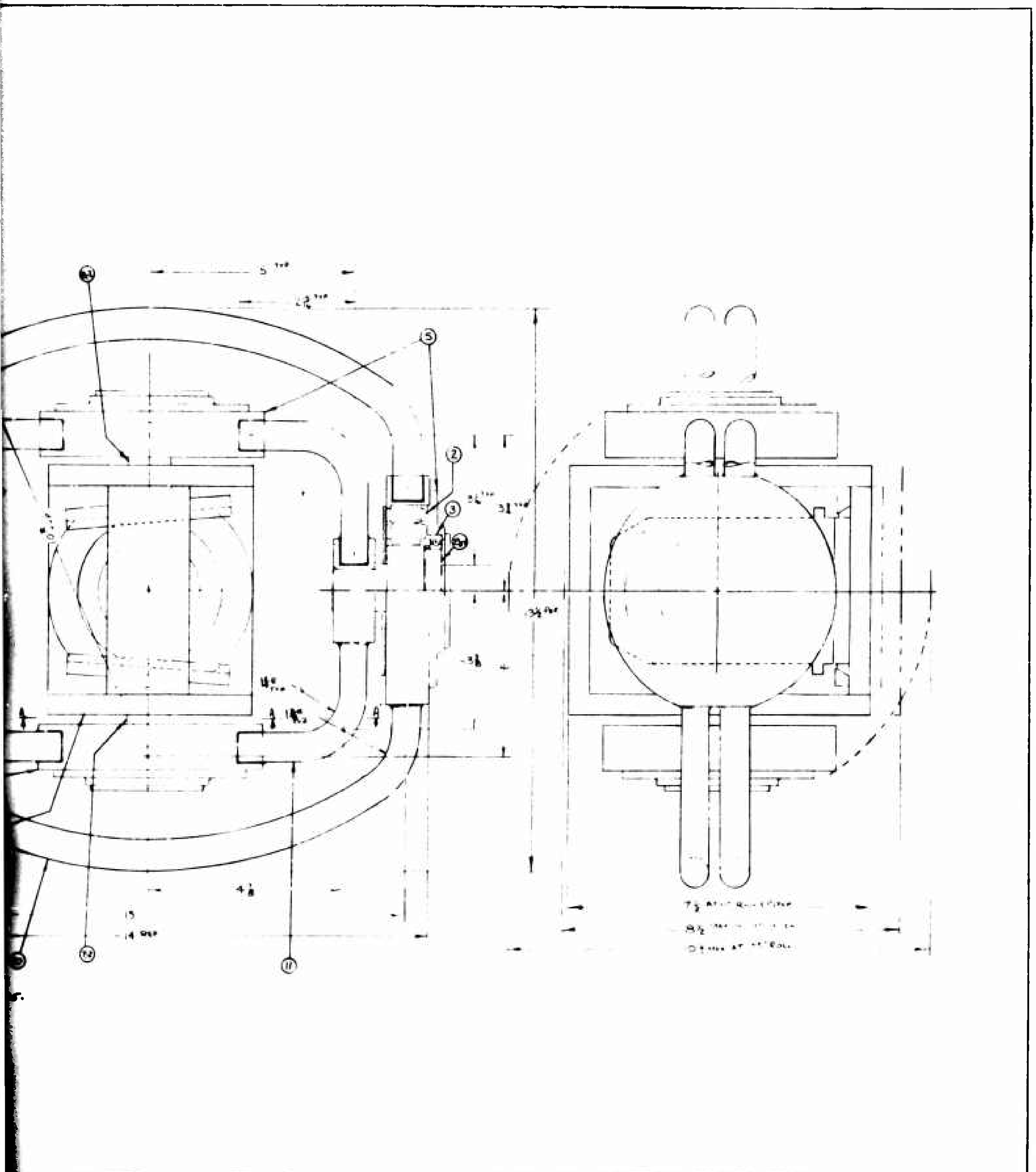
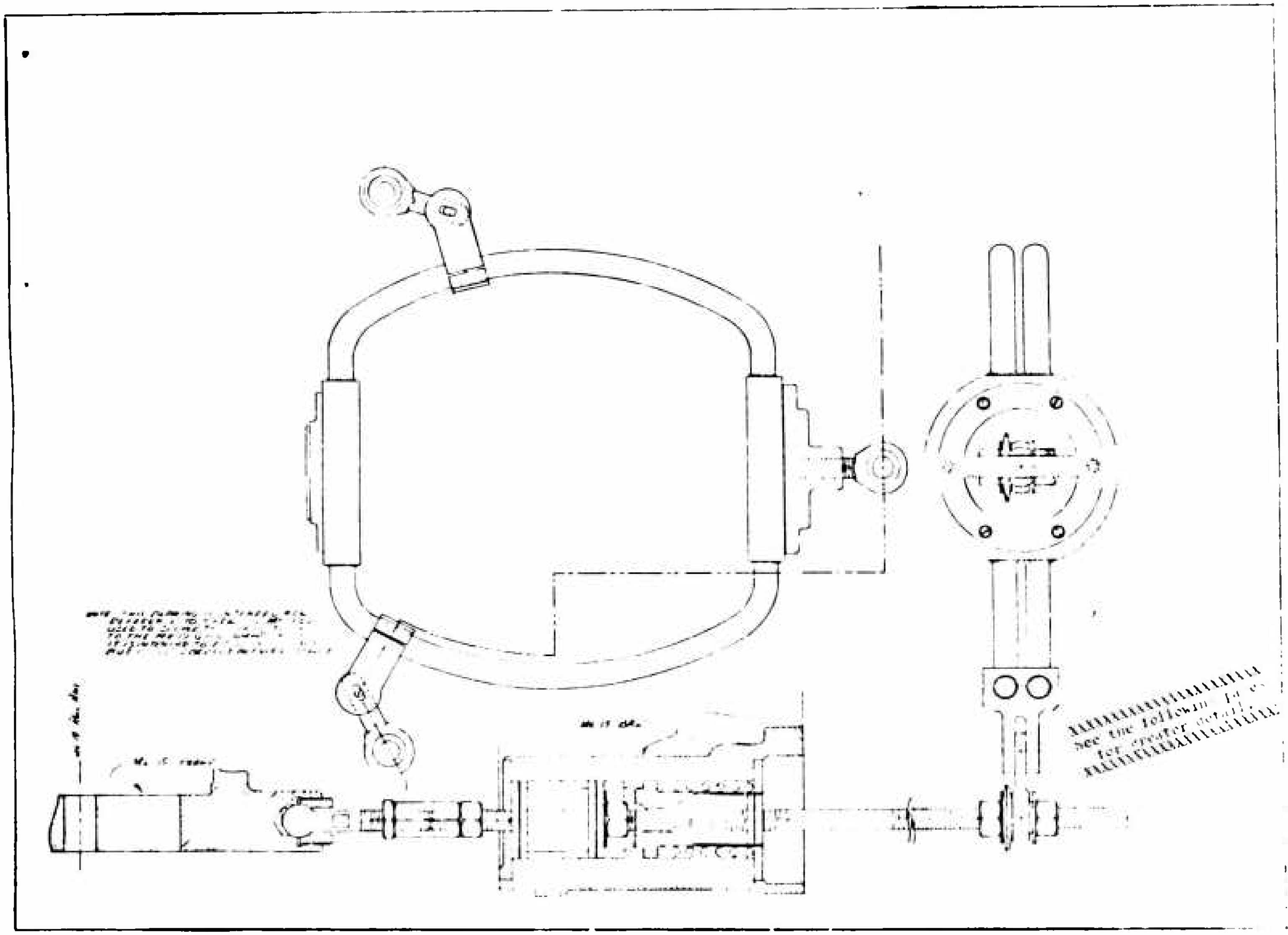
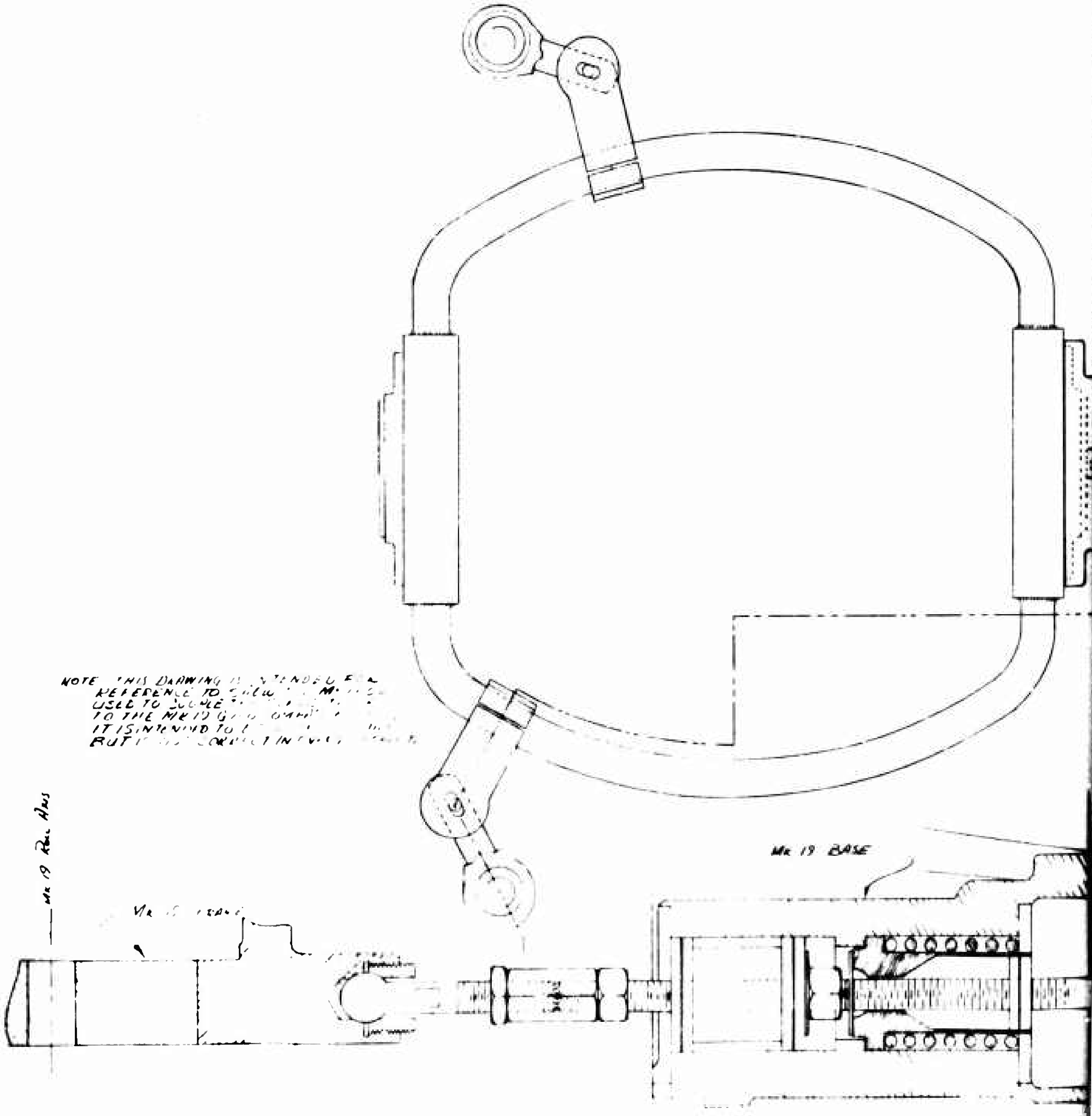


Figure 12.

76.2



27.1 Figure 13. 27.2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REFERENCE TO
USED TO
TO THE MK 19
IT IS INTENDED TO
BUT
MK 19 BASE

Figure 13.

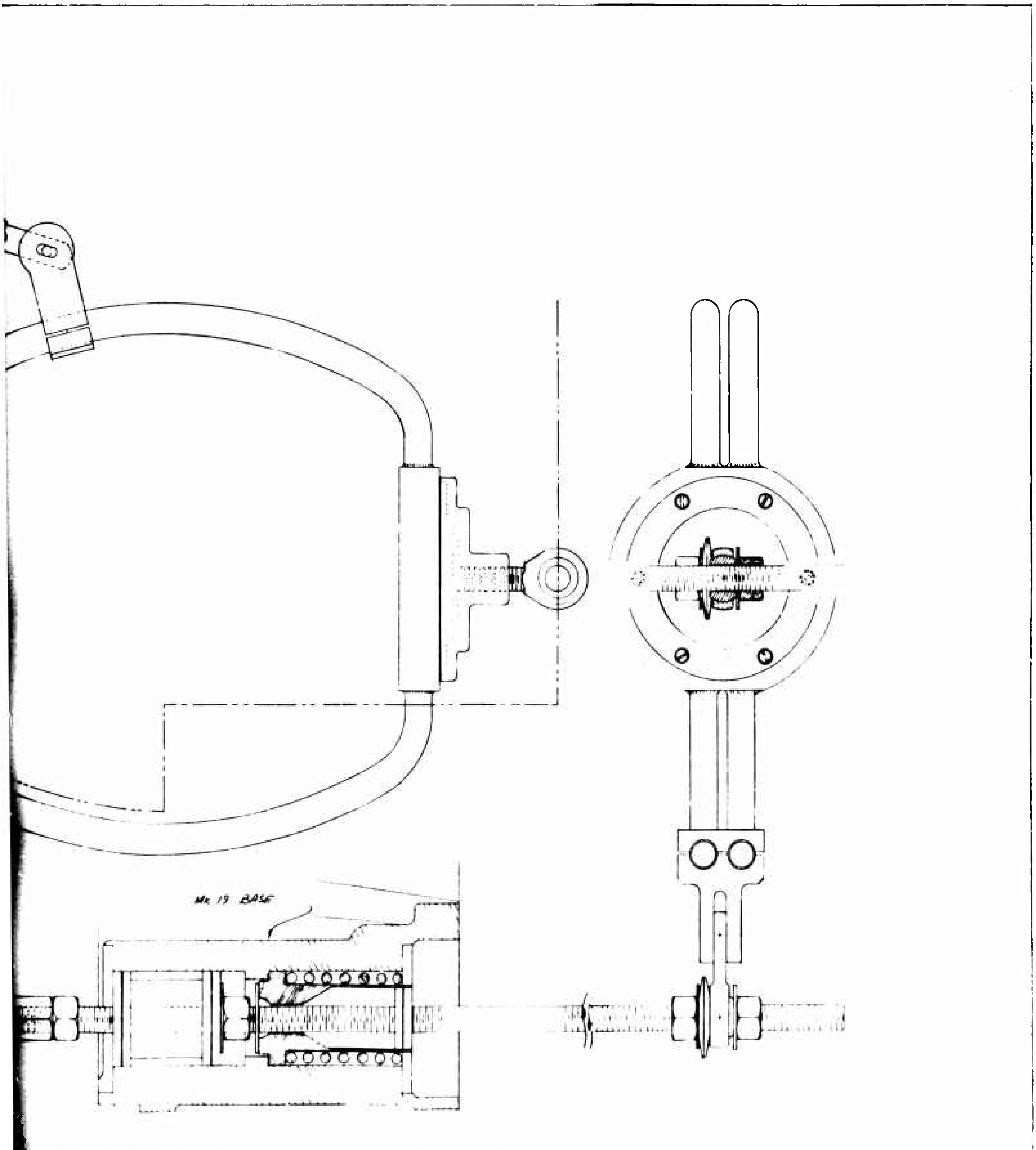

Figure 13.